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THEME A

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Summary

The Kariba dam is undergoing concrete expansion as a result of an alkali-aggregate reaction. The model adopted to simulate the process is explained in the paper; it is based on the model first proposed by Ulm et al, as later modified by Saouma and Perotti. It has been implemented in the commercial finite element code Abaqus and applied to solve the benchmark problem. The parameters of the model were calibrated using the data recorded up to 1995. The calibrated model was then used for predicting the evolution of the dam up to the present date. Apart from this prediction the paper offers a number of conclusions, such as the fact that the stress level appears to have a major influence on the expansion process; and it presents some suggestions to improve the formulation of the benchmark, such as providing temperature data and widening the locations and conditions of the data employed in the calibration.

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1. Introduction

Concrete may undergo long term swelling as a consequence of a number of chemical reactions, including alkali-aggregate reactions (AAR). The effects of this undesired expansion are almost inevitably deleterious for the structure. The understanding and the mathematical representation of these processes are not fully satisfactory as yet, hence the relevance of the problem of chemical swelling as an active field of research.

In this context a benchmark problem was proposed to be addressed as Theme A of the 11th Benchmark Workshop organized by the International Commission on Large Dams (ICOLD). The problem is that of interpreting the movements experienced by the Kariba dam for a certain period of time and making predictions for its future evolution based on that interpretation. The present paper presents the work conducted by the authors in relation with the problem posed.

The benchmark problem was formulated by *Noret & Molin* [1]. There is little point in repeating here the information contained in that document about the Kariba dam and its evolution, but it should be clarified that the data used in the work reported here has been taken exclusively from that document.

Investigations of the AAR problem have taken place at least from the late thirties [2] and many structures are known to suffer from this problem today. In particular it affects a considerable number of concrete dams built towards the middle of the 20th century in many places of the world. The pervasiveness of the problem was illustrated by *Charlwood & Solymar* [3] who listed 104 known cases of alkali–aggregate reactions (AAR) in dams worldwide.

A review of the state-of-the-art is clearly beyond the scope of the present paper. But based on the results of past investigations, it can be concluded that the factors that have a major influence in the swelling process in a general case are the following:

- Material components: reactive aggregates and alkali-rich cements are needed, additives may also influence the process.
- Time elapsed: the formation of a hydrophilic gel is not instantaneous, it has a latency time; also, once formed, its swelling via an alkali-aggregate reaction (AAR) involves a characteristic time.
- Environmental conditions: as in many chemical reactions, temperature accelerates the process and, since swelling occurs by absorbing water, moisture conditions play a significant role as well.
- Stress state: high compressive or tensile stresses may affect swelling because of their effects on water pathways, e.g.: by closing cracks or creating spaces for the expanded gel.

The significance of other factors can be considered smaller in comparison with those listed above.

2. Concrete behaviour and expansion models

Following an extensive literature review, the more promising mathematical formulation appears to be that proposed by *Ulm et al* [4], as subsequently modified and extended by *Saouma & Perotti* [5]. Both theories will be described briefly below, since they will be incorporated into a finite element code and used for analyzing the dam.

The modifications by Saouma and Perotti address the anisotropy of swelling induced by the state of stress, which is known to be an important characteristic of the swelling process in many cases, including the case of the Kariba dam. Other authors like *Baghdadi et al* [6] have made alternative proposals for describing the stress-induced anisotropy of the swelling process, but that by Saouma and Perotti appears to account reasonably well for all the relevant effects and has been adopted here.

Before going into the details of the swelling models, it is worth mentioning that the constitutive behavior assigned to the concrete was a damaged plasticity model for tensile cracking and compressive crushing. It is therefore in this mechanical framework that the expansion is assumed to take place.

2.1 Model by Ulm et al

The model by Ulm et al assumes that the reaction develops following an equation of the type:

$$1-\xi = t_c(\xi,\theta)\frac{\mathrm{d}\xi}{\mathrm{d}t} \tag{1}$$

where ξ is the extent of the reaction, t_c is the characteristic time of the reaction, θ is the absolute temperature, and t is the time elapsed. The characteristic time decreases as the reaction progresses:

$$t_c(\xi,\theta) = \tau_c(\theta)\lambda(\xi,\theta) \tag{2}$$

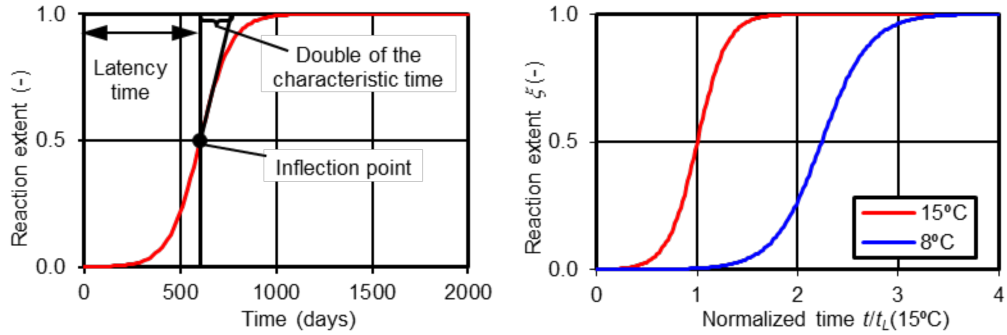
$$\lambda(\xi,\theta) = \frac{1+\exp\left(-\tau_L(\theta)/\tau_c(\theta)\right)}{\xi+\exp\left(-\tau_L(\theta)/\tau_c(\theta)\right)} \tag{3}$$

where τ_c is a characteristic time constant.

The latency and characteristic times are both a function of temperature, following the Arrhenius law that governs thermally activated processes. It may be noticed that the above differential equation can be solved analytically in the isothermal case. The parameters involved in the model, with the values proposed by *Larive* [7], are listed below:

- unidirectional expansion at infinite time: 0 to 0.004
- activation energy of the characteristic time: 5400 ± 500 K
- activation energy of the latency time: 9400 ±500 K

The activation energies are already divided by the Boltzmann constant, thus their K units. Figure 1a shows the physical meaning of the two time constants involved. The latency time is the time elapsed to the point of inflection of the curve that depicts the development of the reaction; it is near, but slightly differs from, the time when 50% of the reaction has taken place. The characteristic time is half of the incremental intercept produced by a tangent drawn at the inflection point. Figure 1b shows the effect of temperature in the progress of the reaction.



a) Reaction extent at constant temperature

b) Effect of temperature

Figure 1: Reaction extent according to Ulm et al

2.2 Model by Saouma and Perotti

The model by Saouma and Perotti was developed to represent the progress of the AAR, taking the temperature dependence from the model by Ulm et al. Saouma and Perotti propose that the effects of the volumetric reaction in one space direction will be affected by the others, that the preferred directions for expansion will be the least compressed ones, and that high normal stresses will influence the reaction through mechanisms such as providing space for gel expansion, sealing or opening pathways for water migration, etc.

The effects of the stress level are reflected through its influence on the latency time:

$$\tau_L(\theta,\bar{\sigma}) = f(\bar{\sigma})\tau_L^{\mathrm{ULM}}(\theta) \tag{4}$$

$$f(\bar{\sigma}) = \begin{cases} 1 & \text{if } \bar{\sigma} \le 0 \\ 1+\alpha\bar{\sigma} & \text{if } \bar{\sigma} > 0 \end{cases} \tag{5}$$

where $\bar{\sigma} = -(\sigma_I + \sigma_{II} + \sigma_{III})/(3f_c)$ is the normalized pressure, α is an empirical coefficient, for which Saouma and Perotti propose using 4/3 based on the tests by *Multon and Toutlemonde* [8], f_c is the compressive strength, and τ_L^{ULM} is the latency time from Ulm et al.

For the evolution of swelling the following equation is proposed:

$$\frac{\mathrm{d}\varepsilon_{\mathrm{vol}}}{\mathrm{d}t} = \Gamma_t(u_{\mathrm{ck}})\Gamma_c(\bar{\sigma})\xi(t,\theta)\varepsilon_{\mathrm{vol}}^{\infty} \tag{6}$$

where Γ_t accounts for the reduction of swelling caused by cracking with crack opening u_{ck}, Γ_c accounts for the reduction of swelling by compression with a normalized pressure $\bar{\sigma}$, and $\varepsilon_{\mathrm{vol}}^{\infty}$ is the free expansion at infinite time.

The dependence on tensile cracking is incorporated by:

$$\Gamma_t(u_{\mathrm{ck}}) = \begin{cases} 1 & \text{if } u_{\mathrm{ck}} \le \gamma_t w_c \\ \Gamma_r + (1-\Gamma_r)\dfrac{\gamma_t w_c}{u_{\mathrm{ck}}} & \text{if } u_{\mathrm{ck}} > \gamma_t w_c \end{cases} \tag{7}$$

where γ_t governs the reduction of expansion in tension, Γ_r is the coefficient of residual expansion in tension, w_c is the maximum crack opening in the tensile softening curve. The effect of compression is introduced as:

$$\Gamma_c(\bar{\sigma}) = \begin{cases} 1 & \text{if } \bar{\sigma} \le 0 \\ 1-\dfrac{e^{\beta}\bar{\sigma}}{1+(e^{\beta}-1)\bar{\sigma}} & \text{if } \bar{\sigma} > 0 \end{cases} \tag{8}$$

where β is an dimensionless parameter.

Apart from determining the volumetric expansion, the model must also distribute it among the three space directions. For example, in uniaxial tension, the amount of chemical swelling would be identical in all directions; but in uniaxial compression, with the stress above a certain threshold σ_u, the chemical expansion would only occur in the two transverse directions. Figure 2 shows how the model distributes the expansion in the various stress states.

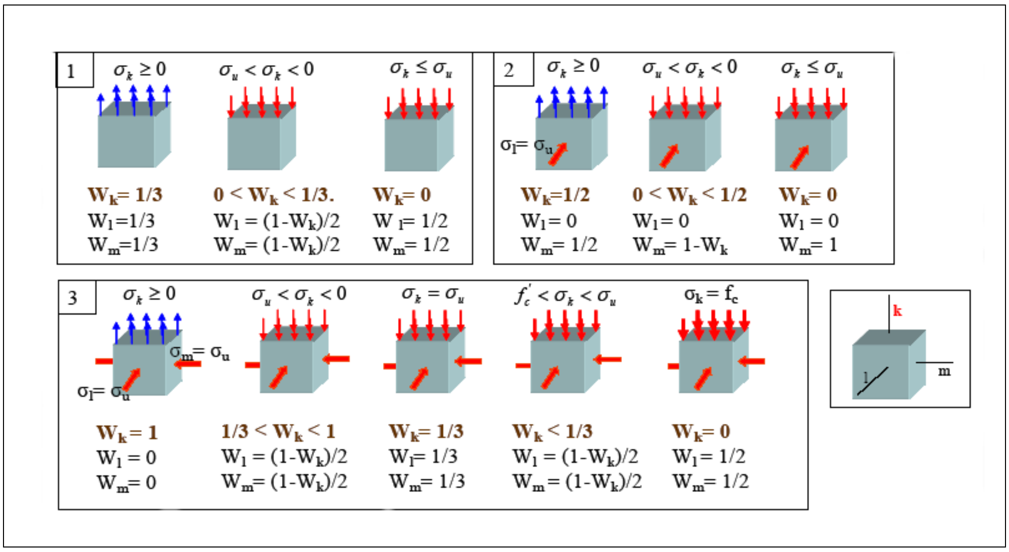


Figure 2: Distribution of expansion after Saouma and Perotti

3. Numerical implementation

The model by Saouma and Perotti described in the previous section was implemented in Abaqus/Standard [9]. For this purpose a user subroutine was created to determine incrementally the imposed deformations caused by both the expansive chemical reaction and thermal dilation. Such increments are a function of temperature, progress of the reaction, pressure, and crack opening.

The calculation requires information about the principal stresses and directions and must be combined with the plasticity and the continuous damage model of the concrete. State and field variables are updated in another user subroutine and moisture is introduced as an independent field variable. The rest of the variables are updated at the beginning of each time step, thus in an explicit scheme, but are extrapolated to mid-step from their most recent values. The size of the time step may therefore play an important role and the sensitivity to this parameter should be studied for each specific application. For cases such as discussed in the present paper, experience indicates that generally 2 weeks is an adequate time step. Other subroutines were also written to impose yearly periodic boundary conditions for thermal analyses and to vary the hydrostatic pressure.

4. Application to the Kariba dam

4.1 Approach adopted

When modeling swelling problems, a rigid connection between concrete and rock would give rise to unrealistic stress concentrations at the interface. This led to adopting the finite element mesh Model2.mesh, excluding the JOIN elements because in Abaqus contact surfaces are defined as element faces. The friction coefficient assumed is 1.4. The mesh, shown in Figure 3, is composed of 1278 second-order brick elements with reduced integration, 238 second-order wedge elements, and 2 second-order tetrahedrons. The total number of variables is 23427.

The stress field at the end of construction is obtained using a reduced elastic modulus in the hoop direction (1% of the real value), thus forcing the dam to behave as a series of independent cantilevers. During this initial phase the dam is tied to the rock because no debonding is expected. The stress field determined is then imported as the initial state for subsequent analyses during operation.

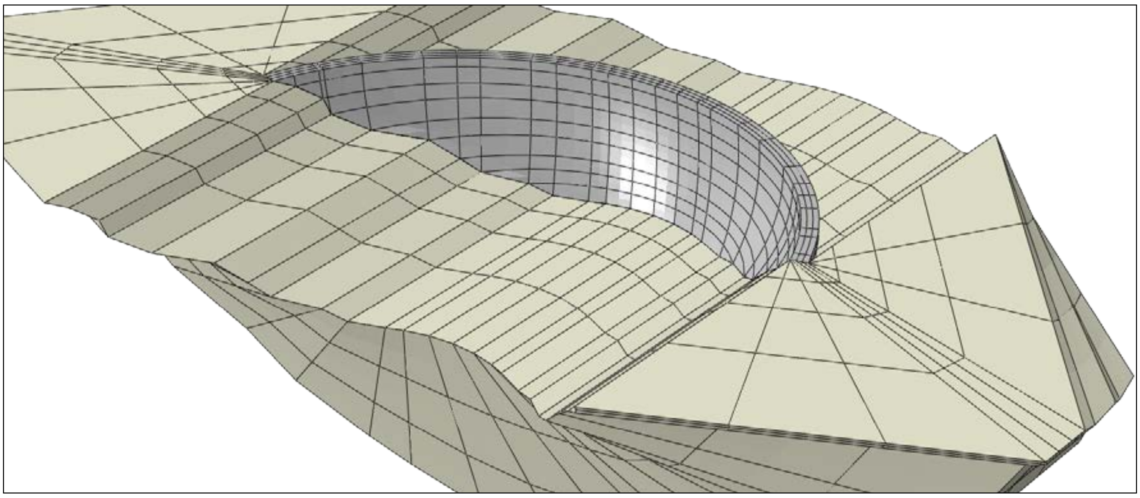


Figure 3: Finite element mesh

The histories of recorded movements provided do not really allow an accurate calibration of any logistic curves, as would be required to estimate the time constants. Because of this difficulty the rate of unidirectional free expansion has been assumed to remain constant over the period of interest. In practice this is equivalent to simplifying the model proposed by Saouma and Perotti to:

$$\frac{\mathrm{d}\varepsilon_{\mathrm{vol}}}{\mathrm{d}t} = \frac{3\Gamma_c(\bar{\sigma})\dot{\varepsilon}_0}{f(\bar{\sigma})} \tag{9}$$

where $\dot{\varepsilon}_0$ is the rate of unidirectional free expansion.

Since most of the concrete would be expected to remain in compression, there is essentially no need to consider the effects of tensile stresses in the expansion. Once the increment of volumetric expansion is determined, it is distributed among the three instantaneous principal directions as in the original model. The compressive and tensile strengths of concrete have been taken as 25 MPa and 2 MPa, respectively.

The values proposed by Saouma and Perotti for the expansion parameters have been adopted, namely α = 4/3 and σ_u = -10 MPa. However, two of the parameters were calibrated based on the data: $\dot{\varepsilon}_0$ and β, the parameter that governs the reduction of expansion with compression. The calibration was based on the data produced during the period 1982-1995 for the radial displacement of target T434 and in the crest leveling survey. The specific time period was selected because at earlier times the evolution may be affected by other phenomena, such as transient temperatures and creep; also, it directly precedes the prediction period and, furthermore, the water levels in the reservoir can be taken to be constant, equal to 479.9 m.

For predicting the evolution during the period 1995-2010, the actual water levels in the reservoir were introduced to the analyses via a user subroutine without any time averaging.

One final consideration is in order. The formulators of the benchmark problem appear to believe that, because ambient temperatures are reasonably constant in the area, any thermal effects on the swelling process can be disregarded. With all due respect to their long experience in analysing the Kariba dam, this hypothesis is unlikely to be a good representation of reality. The process is so sensitive to temperature that minor temperature changes would have noticeable consequences; for example, differences in insolation, which are certain to occur in a double-arch dam, or in the upstream and downstream conditions, would suffice to generate such effects. Good temperature data in the concrete would most probably allow improving the quality of the numerical simulation.

4.2 Results produced

The first results presented are those generated by construction and by imposing the pressure field corresponding to a water level 483.8 m, which represents the average during the initial high level period. The resulting distributions of stresses and displacements are presented in Figures 4 and 5, respectively.

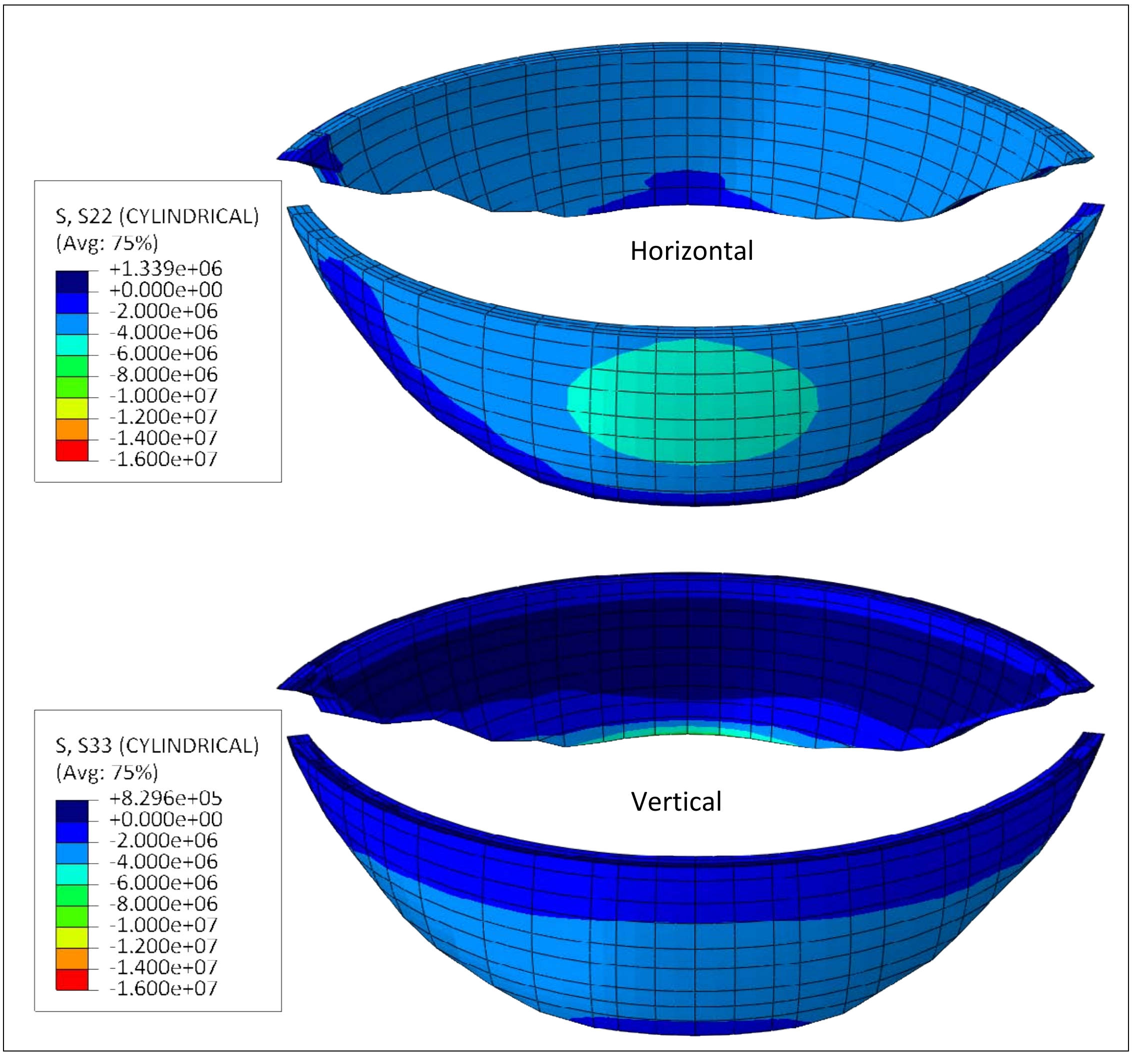


Figure 4: Stresses in 1963 with water level at 483.8 m (Pa)

The parameters of the expansion law are then calibrated using the data from the surveys, assuming the averaged water levels shown in Figure 6. The formulators of the benchmark state that the zero values of the series cannot be considered reliable, thus the curves obtained by simulation can be translated vertically to match the experimental data. In other words, the calibration of the parameters is only based on the slopes of the series, without relying on the zero values.

Using the above strategy, the parameter values that result from the calibration are $\beta = 4$ and $\varepsilon_0 = 39$ $\mu\varepsilon$/year. When those values are used, the calculated and experimental slopes for all the data series are very close over the calibration period, as can be seen in Figures 7 and 8.

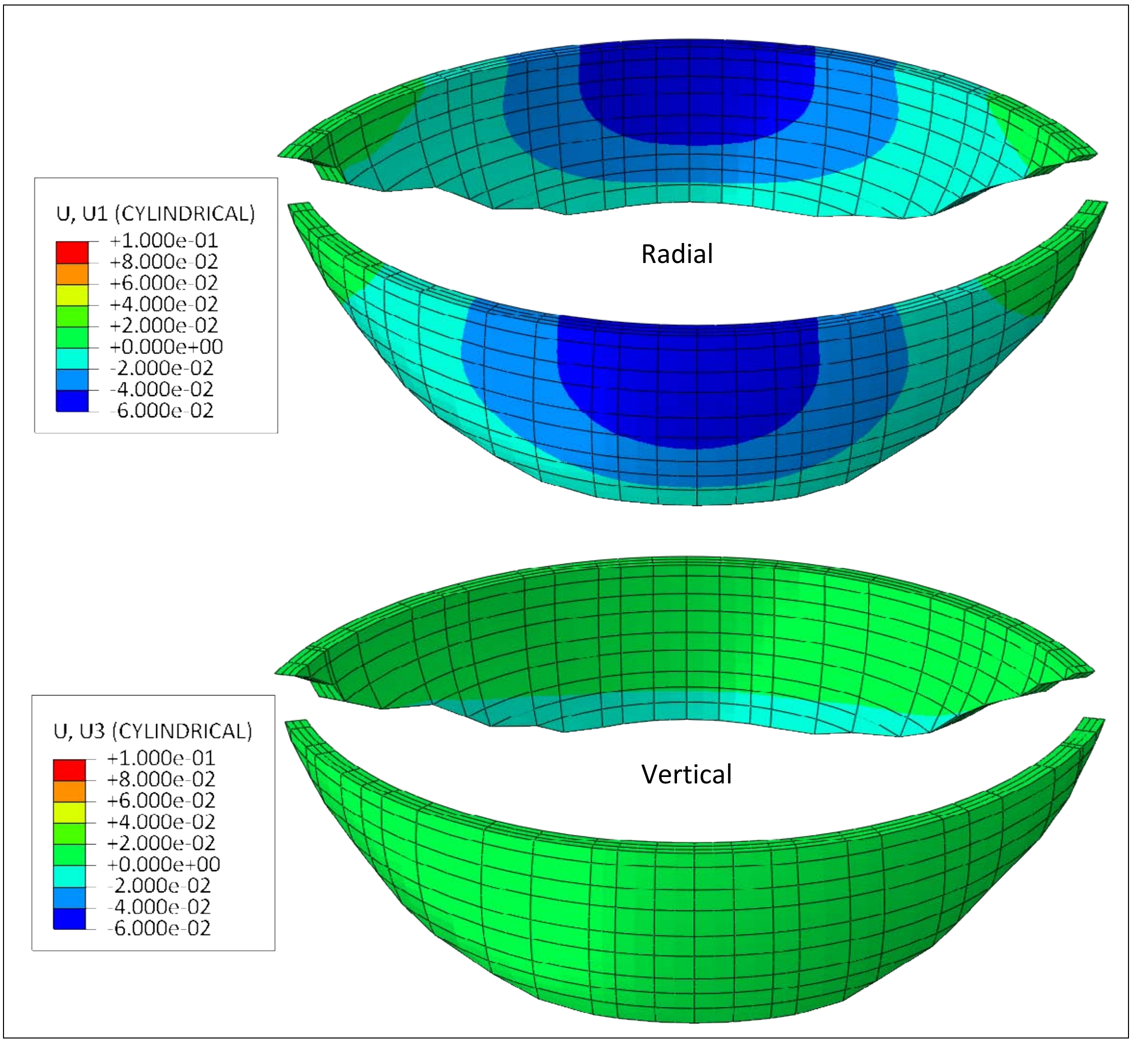


Figure 5: Displacements in 1963 with water level at 483.8 m (m)

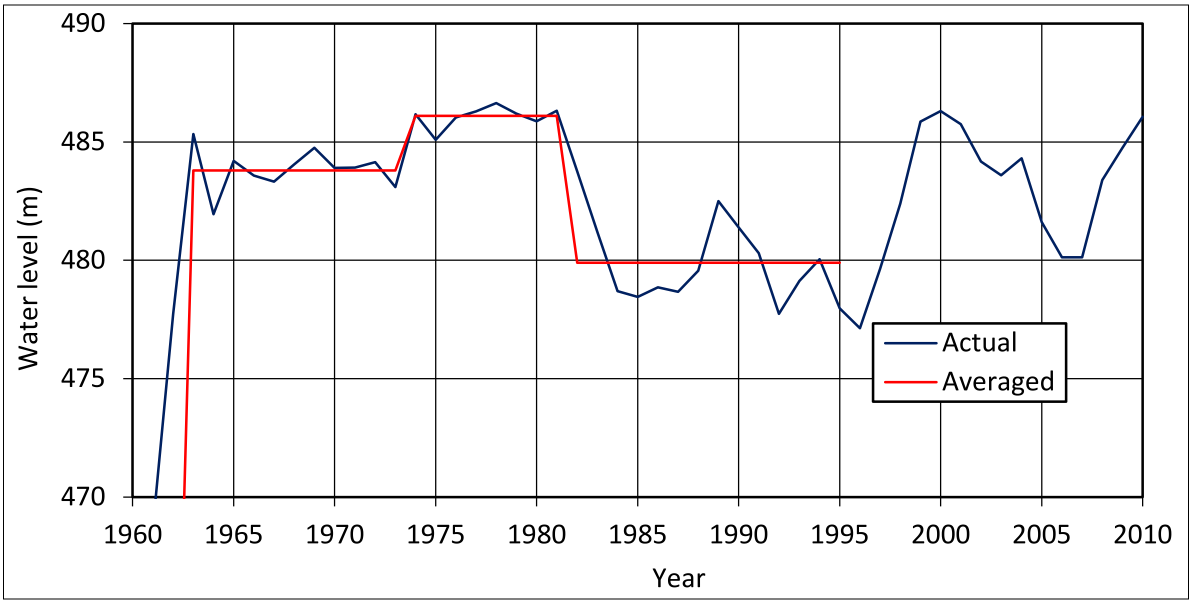


Figure 6: Water level

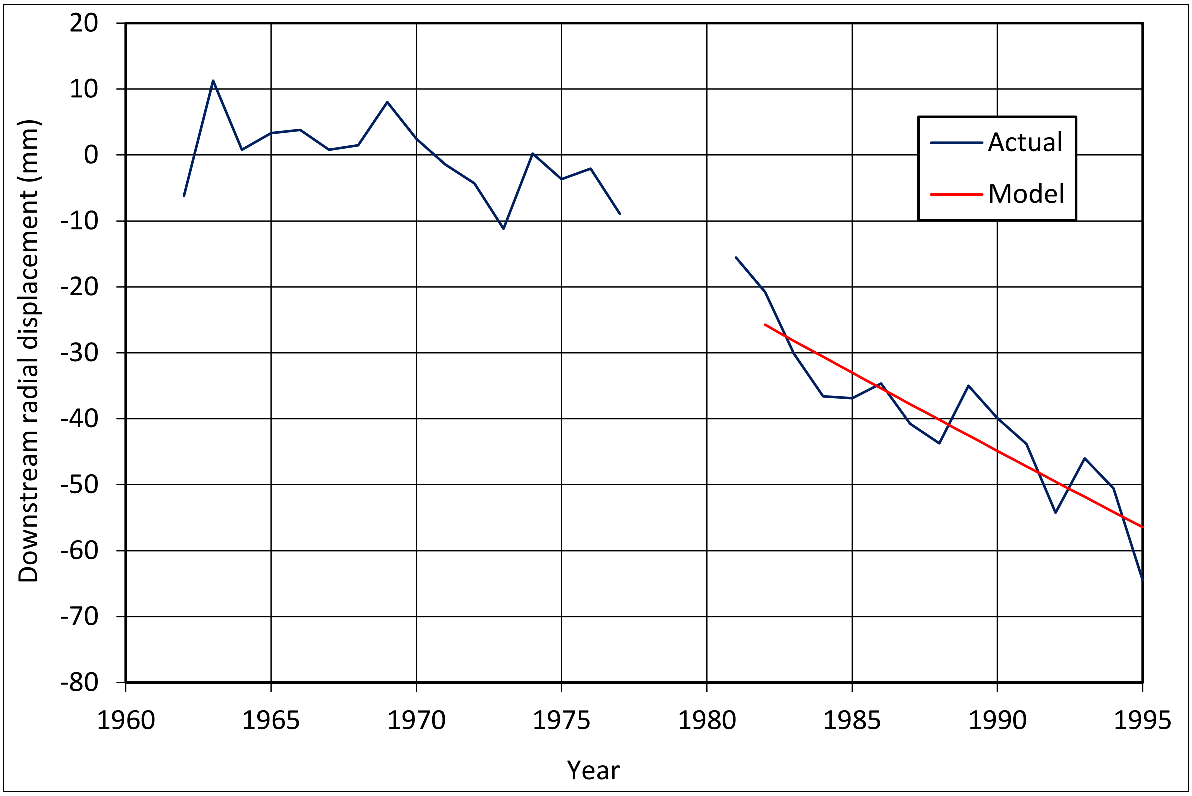


Figure 7: Radial displacements during the calibration period

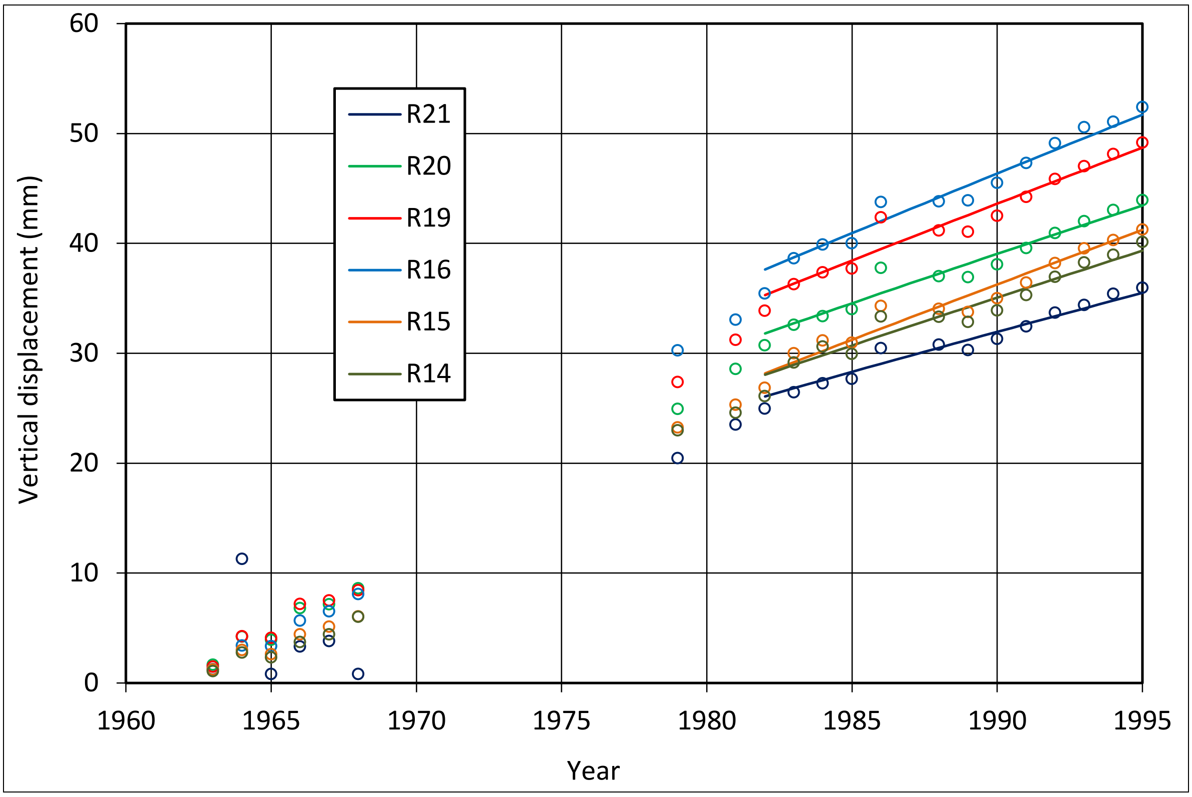


Figure 8: Vertical displacements during the calibration period

It is also of interest to determine, using the calibrated values of the parameters, the rate of unidirectional expansion that would result for concrete cores subjected to different levels of uniaxial compression. The expansion rates calculated are plotted in Figure 9 as a function of the stress level.

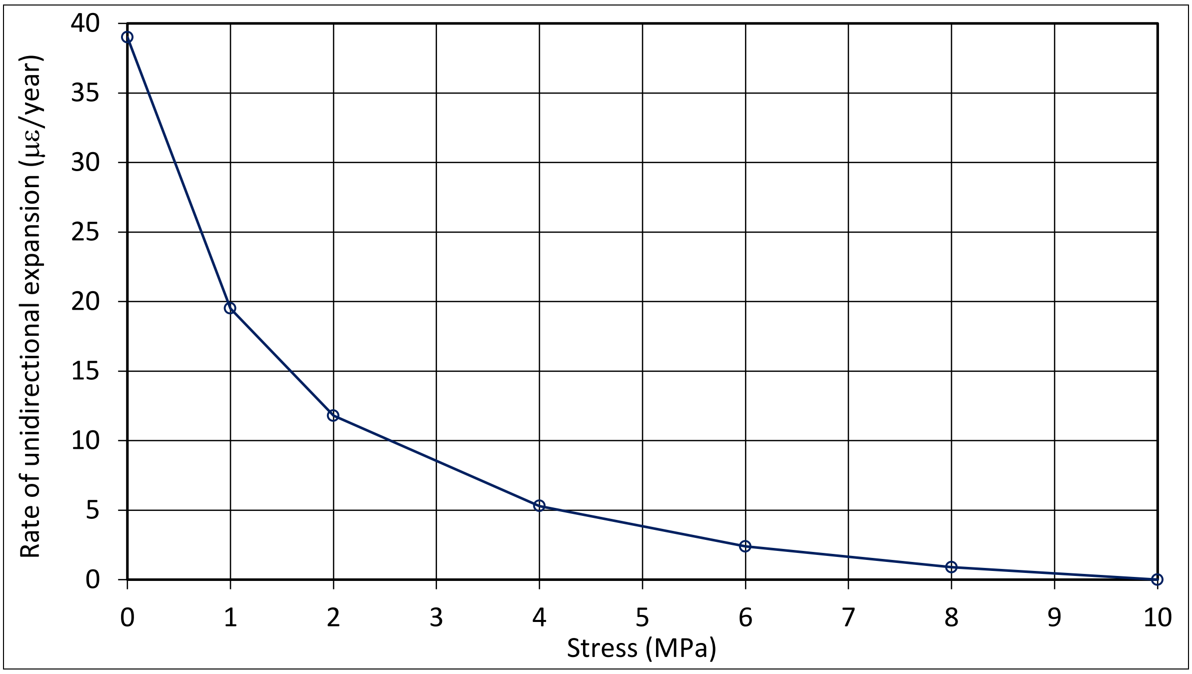


Figure 9: Rate of expansion under compression

Using those values of the calibrated parameters, predictions have also been made as to the likely conditions in 2010. The distributions of stresses and displacements at that time are respectively shown in Figures 10 and 11.

The calculated expansions along the three space directions, again for the year 2010, are provided in Figure 12. As could be expected, those expansions are greater in the radial and vertical directions than in the hoop direction; this is a consequence of the greater levels of compressive stresses that develop in the hoop direction.

The predicted evolution of the radial displacements for the period 1995-2010 is presented in Figure 13. Similarly, the evolution of the various vertical displacements appears in Figure 14 for that same time period.

As a final comment, the amount of information given for conducting the benchmark is considered to be somewhat scarce. The unreliability of the zero values, the lack of temperature data, and the number of locations where data are provided illustrate that scarcity. The end result is that the range of conditions covered by the calibration is relatively narrow, giving the possibility that other models, even some conceptually quite different, might provide a similar match.

5. Conclusions

Having introduced in Abaqus/Standard the simplified expansion model originally described by Ulm et al, including the modifications and expansions later proposed by Saouma and Perotti, its parameters were calibrated to fit the movements detected in the Kariba dam up to 1995. The resulting model was then used to predict the future evolution of the dam.

As a consequence of the work conducted, the following conclusions can be offered:

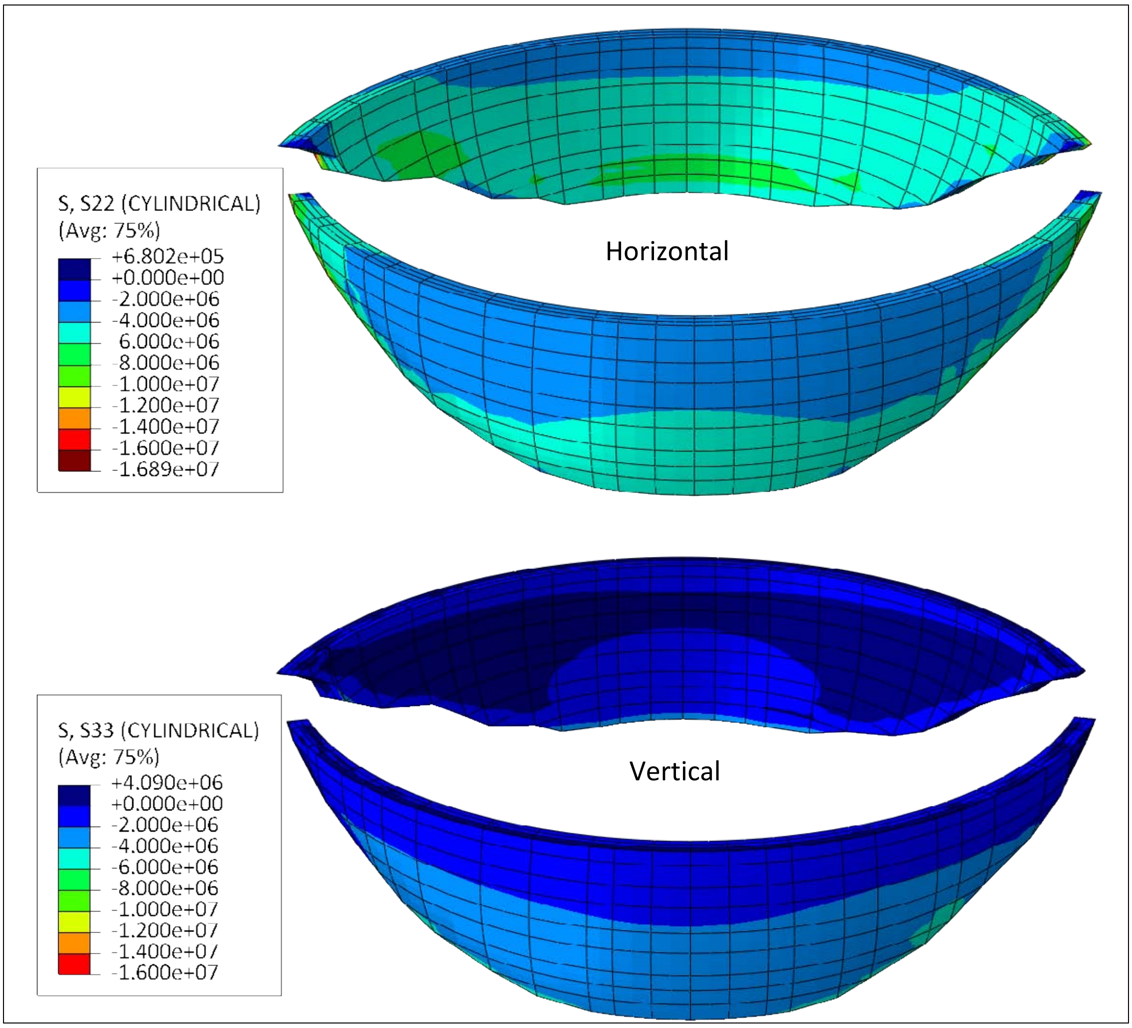


Figure 10: Stresses in 2010 with water level at 482.7 m (Pa)

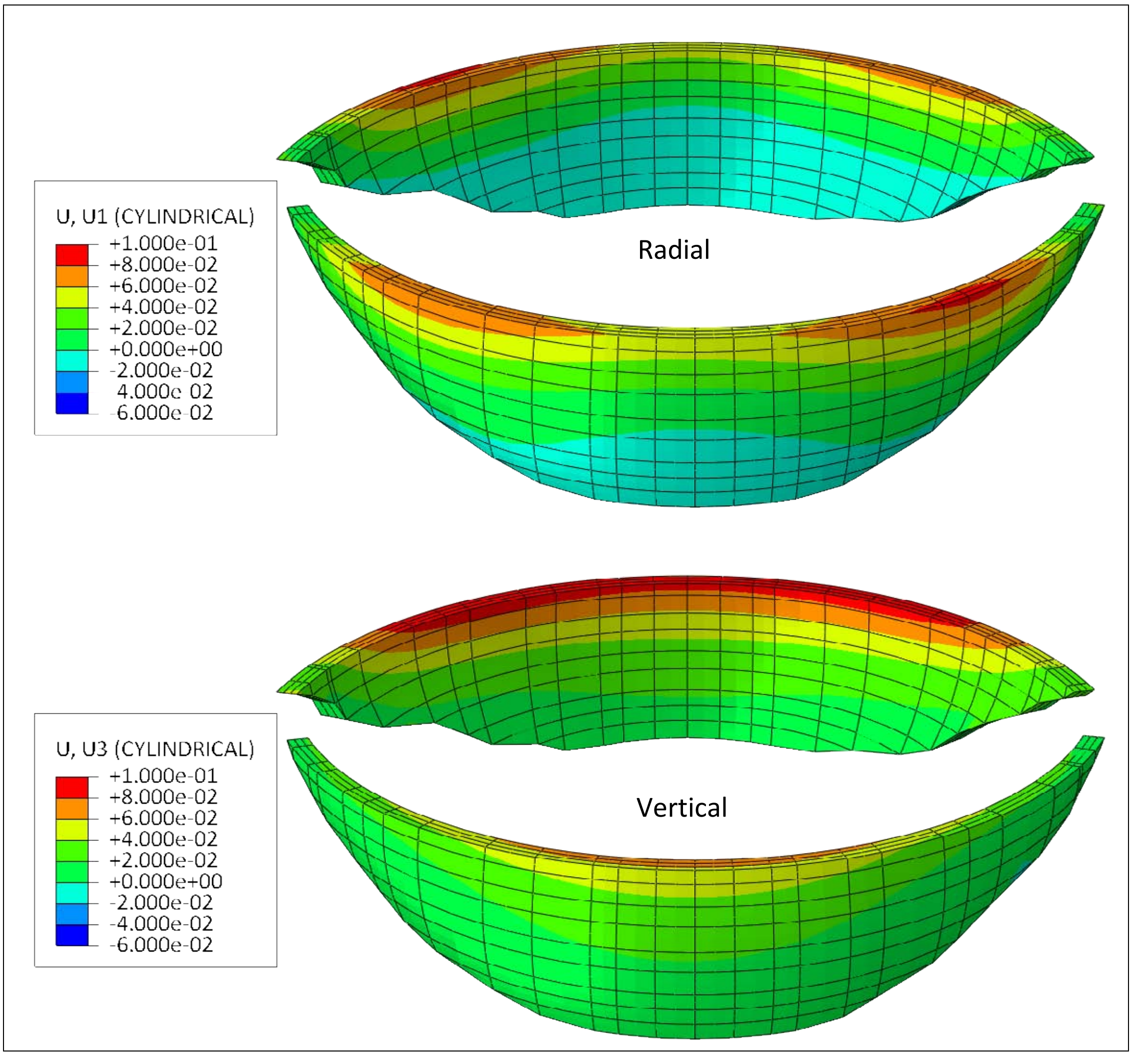


Figure 11: Displacements in 2010 with water level at 482.7 m (m)

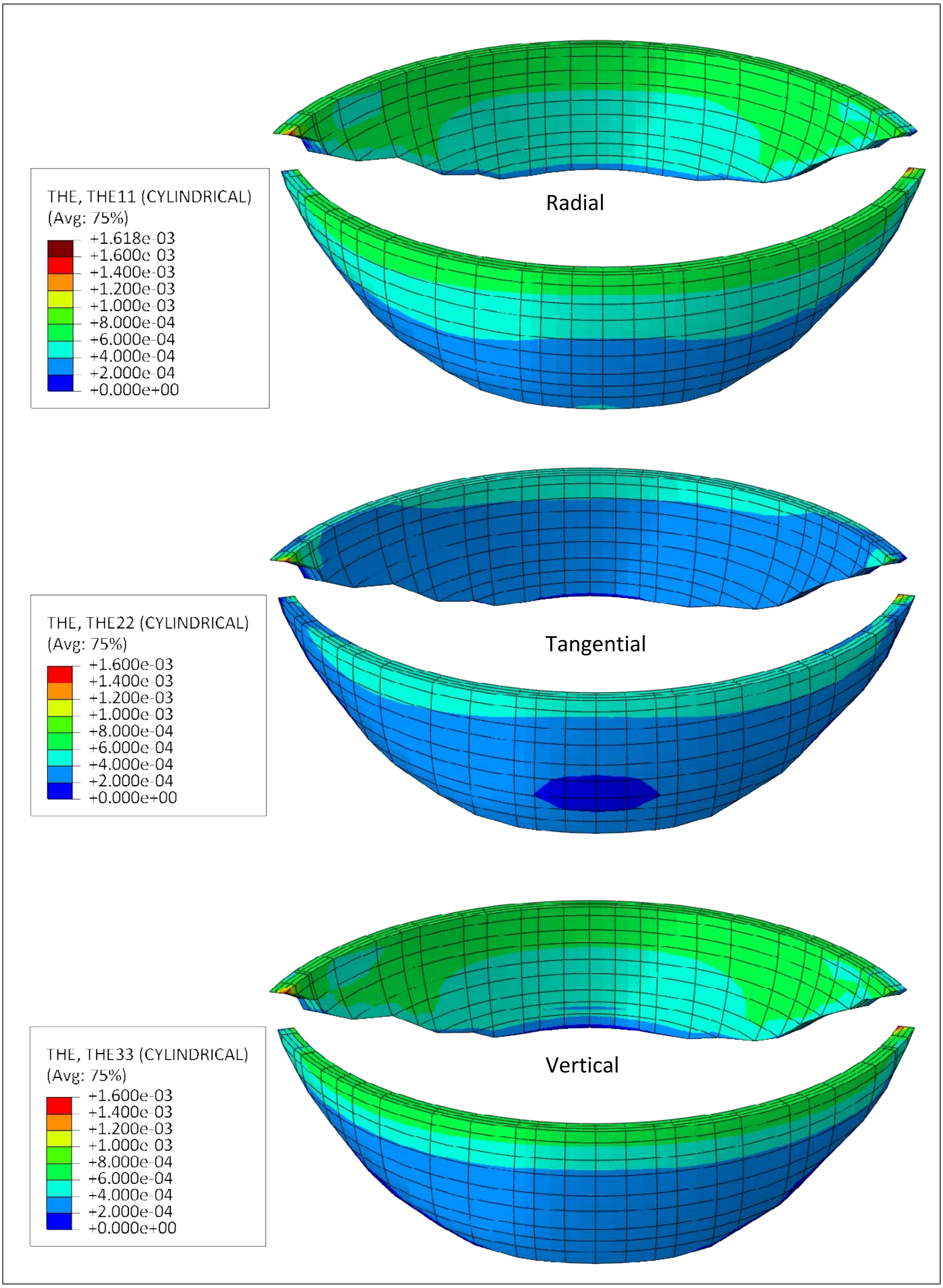


Figure 12: Expansion along each direction in 2010 (-)

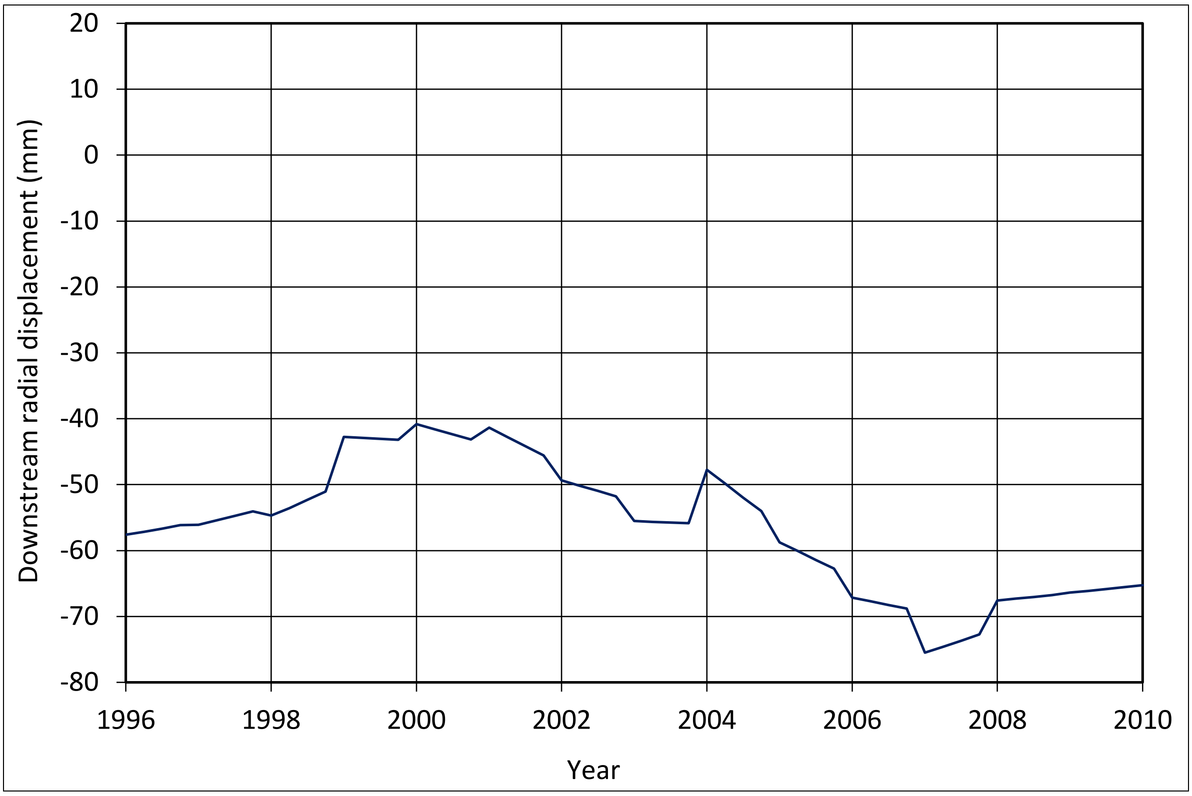


Figure 13: Radial displacements during the prediction period

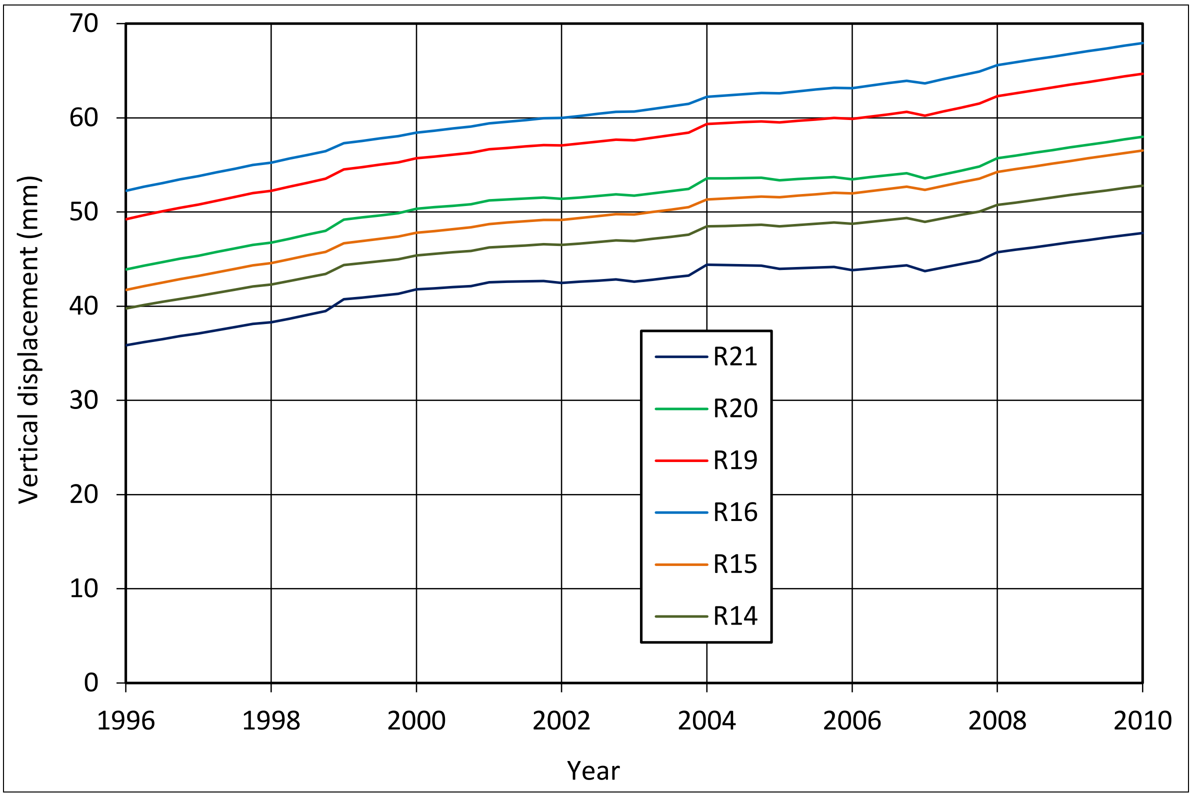


Figure 14: Vertical displacements during the prediction period

- The unidirectional rate of expansion for uncompressed concrete is around 39 $\mu\varepsilon$/year during the periods studied.
- The rate of expansion is very sensitive to the existing level of compression. By way of example the unidirectional rate of expansion decreases to only 5 $\mu\varepsilon$/year under compressive stresses of 4 MPa.
- As a result, the concrete expansion undergone is considerably greater in the radial and vertical directions than in the hoop direction, where expansion leads to a greater levels of compression.

Finally, in spite of the relatively small variation of the local temperatures during the year, it is suspected that these may play a non negligible role. The process is so sensitive that minor temperature changes would have noticeable consequences; for example, differences in insolation, which are certain to occur in a double-arch dam, or in the upstream and downstream conditions, would suffice to generate such effects. Good temperature data in the concrete would most probably allow improving the quality of the numerical simulation. The calibration would also improve if the data supplied covered a wider range of conditions.

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